BREAKTHROUGHS IN LOW-PROFILE LEAKY-WAVE HPM ANTENNAS

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This report describes progress during the 6th quarter of this program and summarizes the current status of the research. Our primary technical activities this period included further investigation of designs with innovative apertures and presentation of our work at the 17th annual DEPS conference.

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Table of Contents

1. INTRODUCTION 4
1.1. Overview of Previous Activities (1^{st} thru 5^{th} Quarter).......... 4
1.2. Overview of Recent Activities (6^{th} Quarter).......... 5
2. STATUS OF THE PLAN/SCHEDULE AND FUNDING.......... 5
3. RESEARCH AND ACTIVITIES PERFORMED THIS PERIOD.......... 7
3.1. Continuing Research. Preliminary 3D full-wave BAWSEA model. 7
4. DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS.......... 11

List of Figures

Figure 1. Updated Program Plan 6
Figure 2. Example of a Single-channel BAWSEA (3D Comsol Multiphysics model) 8
Figure 3. Example of a Four-channel BAWSEA (3D Comsol Multiphysics model) 8
Figure 4. Perspective views of the four-channel BAWSEA example 9
Figure 5. Predicted VSWR (effective) vs Frequency for the example 4-chan BAWSEA. 9
Figure 6. Comparison of Predicted Gain (left) and Aperture Efficiency (right) for the example 4-chan BAWSEA and our earlier recommended-design for a 4-channel FAWSEA. 10

1. INTRODUCTION

This is SARA's 6th Quarterly Report for "Breakthroughs in Low-profile Leaky-Wave HPM Antennas," a 37-month Basic Research effort sponsored by the US Office of Naval Research (ONR). This work includes fundamental theoretical analyses, numerical modeling, and related basic research. Objectives include to discover, identify, investigate, characterize, quantify, and document the performance, behavior, and design of innovative High Power Microwave (HPM, GW-class) antennas of the *forward-traveling, fast-wave, leaky-wave* class.

1.1. Overview of Previous Activities (1st thru 5th Quarter)

During the *first* quarter, we prepared and established useful equations and algorithms for predicting reflections and transmission of incident TE waves from parallel-wire grills, dielectric windows, and combinations of wire grills with dielectric windows, in problems reducible to purely H-plane (2D) representations. We then applied this theory to guide the design of high-gain configurations (again, limited to 2D, H-plane representations) for linear, forward traveling-wave, leaky-wave antennas. The theory built upon equivalent circuit methods and wave matrix theory, which provided useful formalisms upon which we continue to build.

During the *second* quarter, we pursued initial extensions of the previous work into three dimensions, in order to include phenomena with E-plane dependencies. We succeeded in adding into the wave-matrix formalism the reflection/transmission properties associated with the transition to free space from a *finite-width* leaky-wave channel, including the edge-tapering essential to HPM applications. These geometric aspects do not arise in analyses confined to the H-plane alone. Our 3D analyses were somewhat more reliant on numerical models than in the 2D analyses, due to the greater complexity of identifying and/or building practical analytic approaches capable of addressing true 3D geometries of interest.

During the *third* quarter, we explored channel-to-channel coupling (aka, mutual coupling) which (as we have noted earlier) is an important design concern, since it can impact antenna performance significantly in terms of gain, peak power-handling, and impedance matching. Our approach leveraged mostly numerical methods, along with some intuitive arguments, as we explored designs exhibiting different degrees of mutual coupling between adjacent channels. As past and current antenna literature attest, mutual coupling analyses are non-trivial; suffice to say, there is still much work to be done in this area.

During the *fourth* quarter, we continued to study and employ wave-matrix based methods, but with less success than before in applying this approach to *improve* or *optimize* the initial designs. The formalism itself is still valid, but offers reduced practical rewards once an *initial* (i.e., not fully-optimized) geometry (e.g., grill, window, channel depth, etc.) is derived from the more basic-level principles. At that stage, we are finding that further optimization is currently best proceeding via numerical means. Additional work in the fourth quarter led us to identify *new aperture geometries* of potentially-significant practical value, which included the "BAWSEA" and "GAWSEA". These configurations may significantly extend the utility of leaky-wave antenna technology to support integration on more challenging platforms.

During the *fifth* quarter, we designed, analyzed, and documented representative high-performance FAWSEA and CAWSEA antennas suitable for designation as "standard" or "recommended." The configurations we described were scalable with wavelength. These are the initial entries in a library of antennas that will continue to be built throughout this program.

For more information, we encourage the reader to refer our earlier *Quarterly Reports #1* thru *#5*.

1.2. Overview of Recent Activities (6th Quarter)

Highlights of activities this quarter included: (1) our presentation of "Advances in Low-Profile Leaky-Wave Conformable Antennas for HPM Applications" at the 17th Annual Directed Energy Professional Society (DEPS) Symposium in Anaheim, CA, on March 4th, and (2) additional investigation of designs to support the newer curved apertures, especially the "Bent Aperture Waveguide Sidewall-emitting Antenna" (BAWSEA).

Section 3 describes the technical work mentioned above in more detail.

2. STATUS OF THE PLAN/SCHEDULE AND FUNDING

Figure 1 (next page) maps out the updated program plan, for quick reference. During this last quarter, in regard to the analyses tasks (Tasks {2.x}), we shifted our attention toward some of the interesting questions posed by the new BAWSEA configuration (in the "new designs" Task 2.5) at the expense of Tasks 2.3-2.4. We will need to return to those tasks. It is also evident to us, from recent interactions with others in the DEW community, that RAWSEA configurations (which, it should be noted, should also be realizable with singly-curved or multiply-curved apertures) may actually represent the most important subset of these antennas, since they exhibit the lowest-profiles. Regardless, there is still much work ahead to design, optimize, and document the details of these many antennas, as the R&D continues.

The subject contract was awarded on 9/18/2013 and has an end date of 10/17/2016. The total contract value is $868,350, with current (per P00003 signed on 4/24/2014) allotted funding of $406,530. According to SARA's accounting system, as of March 13, 2015, expenses and commitments (including fee) totaled $402,539, thus leaving only $3,990 available, as of that date. If one simply compares the calendar and spending on this project, we have now consumed ~48% of the calendar and ~46% of the total contract value. We have recently been informed by ONR that additional funding is imminent. We thank ONR for supporting this project.

There are no technical, schedule, or other funding-related program problems/concerns to report at this time.

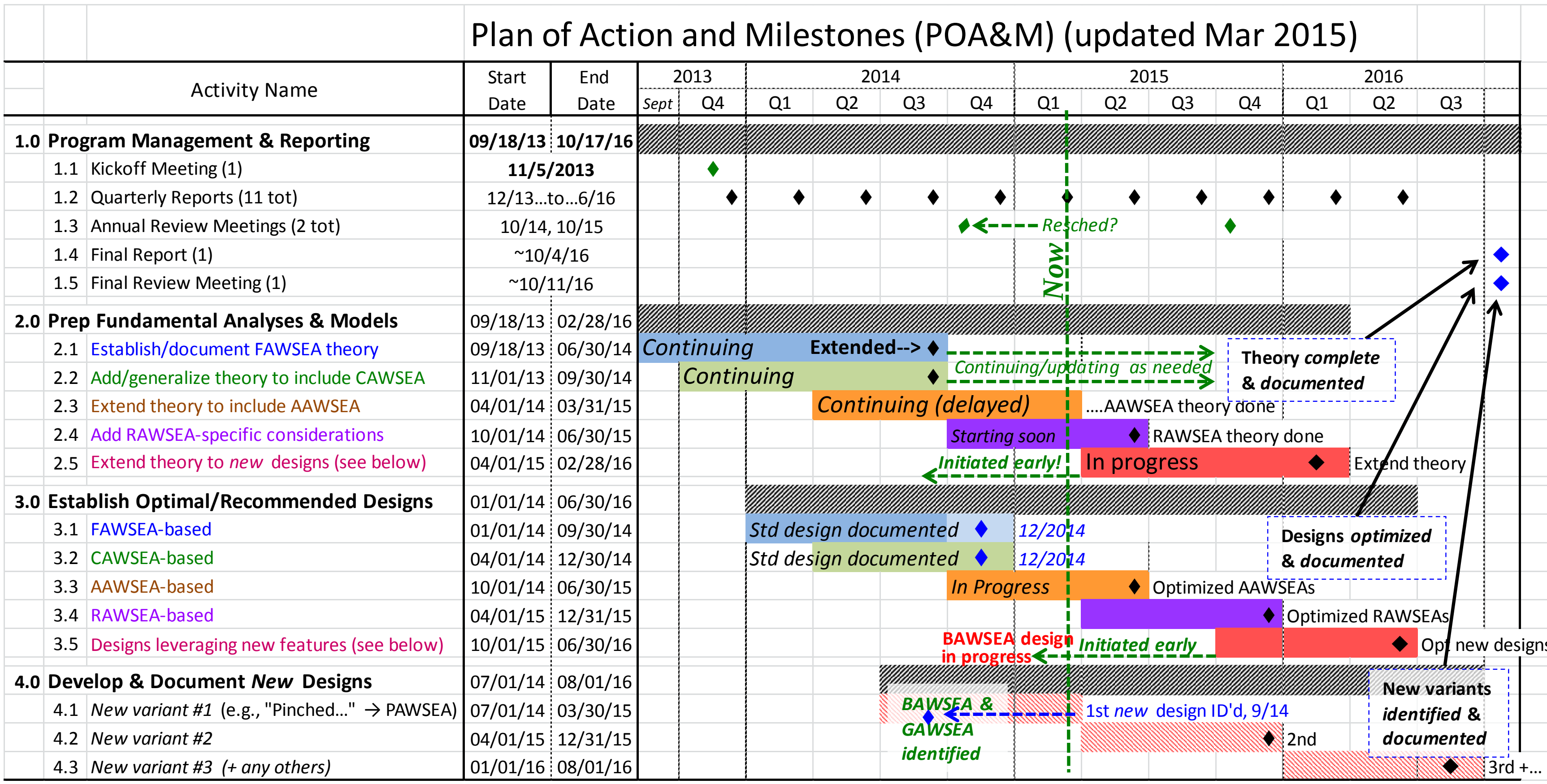

Figure 1. Updated Program Plan

3. RESEARCH AND ACTIVITIES PERFORMED THIS PERIOD

Our presentation at the 17th Annual DEPS Symposium[1] held in Anaheim, CA, on March 4, 2015, publicly summarized our work on this program to date. Our talk was well-attended and well-received and has led to useful follow-up conversations with others in both industry and the DoD. Our slides were provided to ONR in advance of the presentation and were cleared for public release. Readers of this report who would like a copy of their own may request one from SARA (rkoslover@sara.com) or ONR (joong.kim@navy.mil) .

3.1. Continuing Research. Preliminary 3D full-wave BAWSEA model.

The newest variations of HPM-capable leaky-wave antennas (BAWSEA and GAWSEA) noted in our 4th periodic report represent interesting opportunities, but also increased challenges in the development of straightforward and general design guidelines. Recall that the design of a simple FAWSEA can proceed in a series of steps that begins with a set of equations and scripts (as derived from circuit approximations, such as provided by N. Marcuvitz), followed by 2D numerical models that quickly lead to good approximations for the effective distributions of grill wires in 3D. These simplified analyses (both analytic and numerical) can also include a dielectric window (as noted earlier, with generalization to the wave-matrix method). Our next step in the FAWSEA design is/was to generate a 3D single-channel building-block, which accounted for the effects of finite channel-width, aperture flare, and more realistic window shapes, then iteratively tuning-up the performance of this single-channel FAWSEA via appropriate geometric tweaks and analyses via a full-wave 3D modeling code. Admittedly, such a single-channel model leaves out channel-to-channel coupling, but is otherwise very useful.

The single-channel building blocks designed via the above approach helped us create "recommended" designs for multi-channel (especially 4-channel) FAWSEAs and CAWSEAs, which we reported previously (5th Quarterly report). But only some of the features of these building blocks are generalizable to a BAWSEA. For a BAWSEA, the wire-grills generated via our circuit-models and wave-matrix approach cannot be further tested/improved within 2D numerical models, but rather, require a 3D model with no convenient symmetry plane. This makes the design/optimization process for a BAWSEA more computationally-intensive. Likewise, the geometries of neighboring channels of a BAWSEA will (with some exceptions[2]) not be identical when seeking to achieve optimal performance, since the different channels will (in the most general case) have different curvatures and lengths. Despite these challenges, *we are pleased to report that we have achieved some success*, as the examples below will indicate.

Figure 2 shows a single-channel BAWSEA with a 60^o bend, while Figure 3 shows a more ambitious example: a four-channel BAWSEA. We will focus on the latter here. The 4-channel version has wire grills for each channel that are *different*. The wire spacings are fixed, but the number and diameters of the wires are customized to each channel in accordance with the different channel lengths, plus our attempts to meet the phasing criteria described earlier (in our 4th Quarterly report). A couple of perspective views of this 4-channel example are provided in Figure 4. These four channels should, ideally, *not* be fed by identical power inputs, but rather (in this particular BAWSEA) be scaled as follows in overall input power, from innermost to outermost guides: 21.27%, 23.76%, 26.24%, and 28.73%. (For *idealized* leaky grills in this geometry, that uneven distribution should lead to an aperture with the ~most uniform |E|.)

[1] For more about the DEPS symposium, see http://www.deps.org/DEPSpages/DEsymp15.html

[2] Note that a BAWSEA composed of ~identical parallel channels (including with identical radii of curvature) should also be possible, and may be practical. We may explore and describe that alternative configuration in a later report.

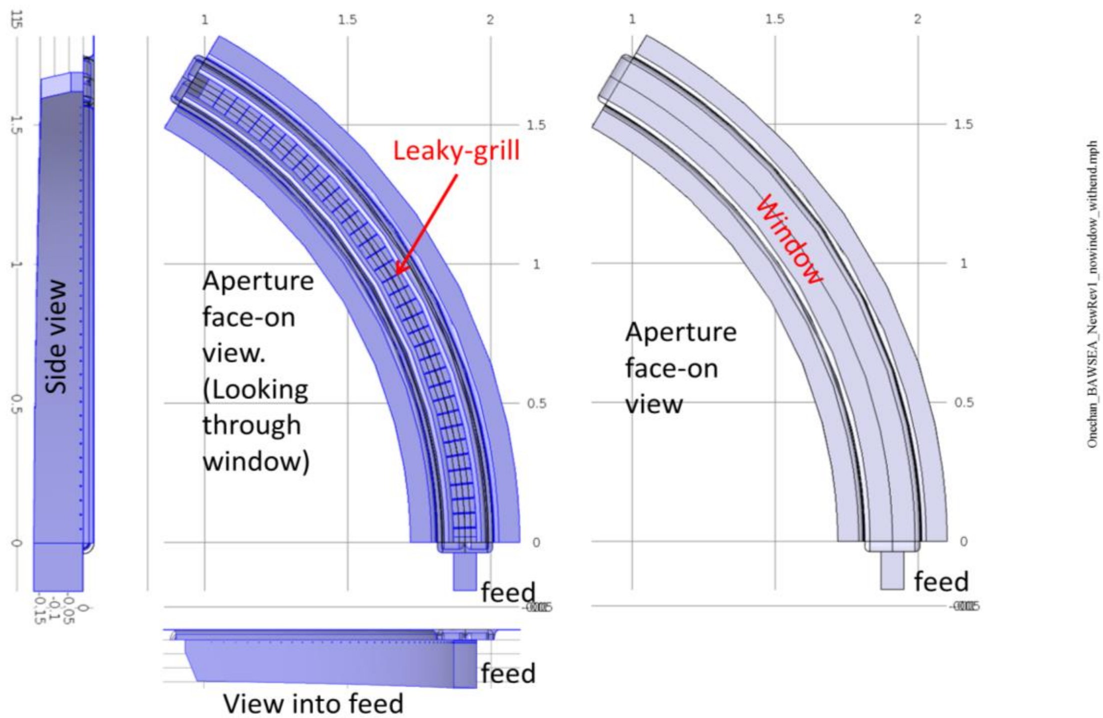

Figure 2. Example of a Single-channel BAWSEA (3D Comsol Multiphysics model)

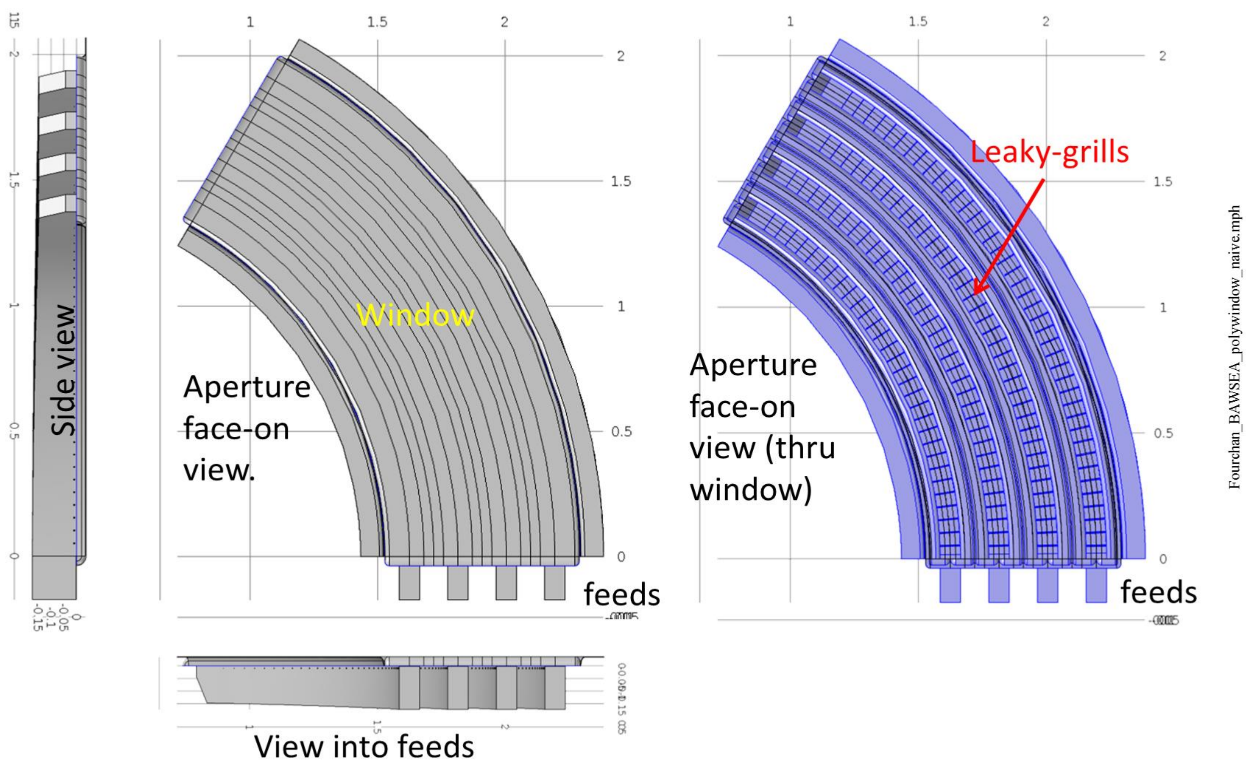

Figure 3. Example of a Four-channel BAWSEA (3D Comsol Multiphysics model)

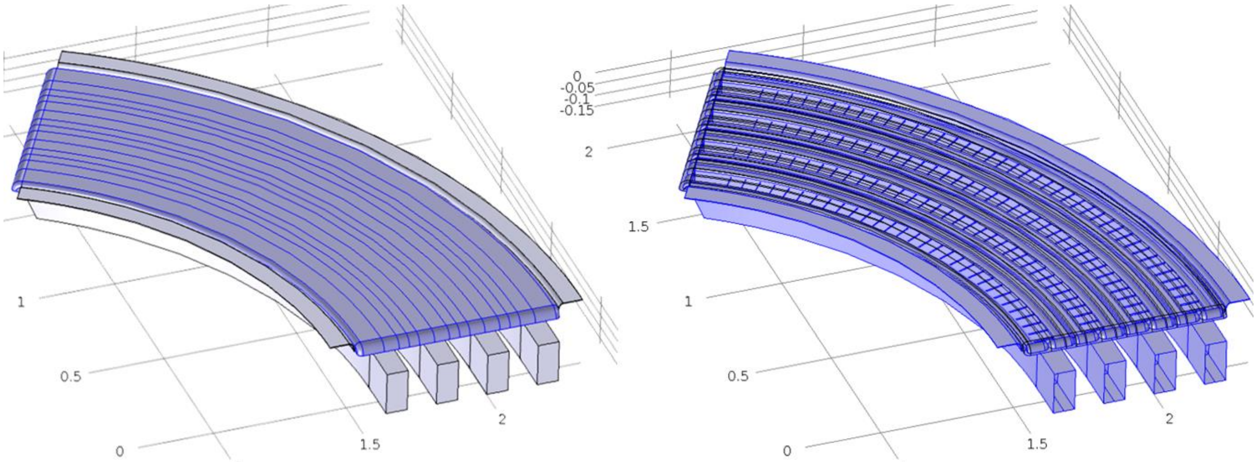

Figure 4. Perspective views of the four-channel BAWSEA example.

Predicted effective VSWR (derived from overall reflected vs. incident power) vs frequency for this BAWSEA is shown in Figure 5. (As with the other forward traveling-wave, leaky-wave antenna designs, this one likewise offers excellent VSWR bandwidth.)

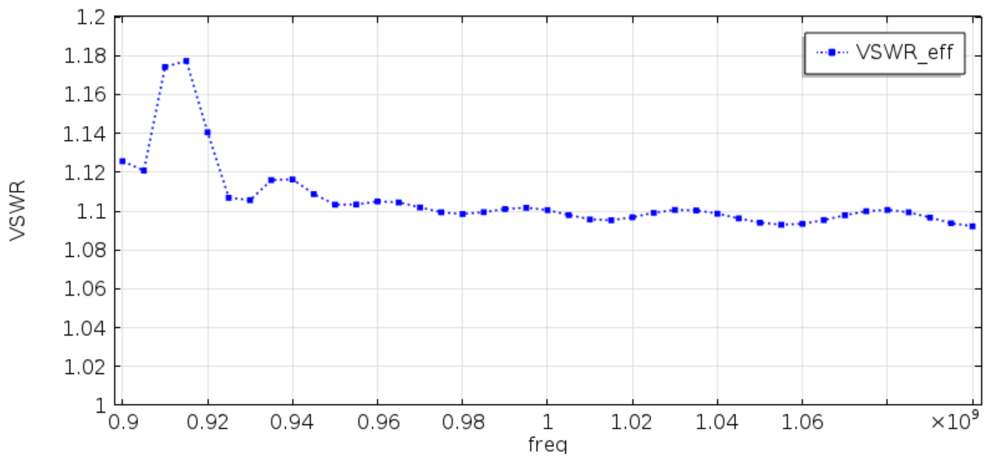

Figure 5. Predicted VSWR (effective) vs Frequency for the example 4-chan BAWSEA.

Of course, it is especially useful to compare the predicted gain of the example 4-channel BAWSEA to that of our earlier "recommended" design (see previous report) for a 4-channel FAWSEA. In fact, the example 4-chan BAWSEA shown here was designed to exhibit nearly the same aperture area and to operate at the same center frequency as that aforementioned FAWSEA, specifically to ease such a comparison. The channel widths and center-to-center separations are also the same (although this does not guarantee comparable channel-to-channel coupling) and the window cross-section is also very similar. Figure 6 provides a comparison of 3D model-predicted gain and aperture efficiency, from $0.9f_0$ to $1.1f_0$. At the center design frequency (f_0), we see that this BAWSEA should deliver only about 1dB less gain than the (very high performing) FAWSEA. This corresponds to a BAWSEA aperture efficiency of about 65%. Needless to say, that is very respectable. Indeed, it is *better* than that of the 4-chan, compensated CAWSEA that we recommend to fit typical cylindrical apertures. So we are very enthusiastic about the additional platform-conformal opportunities that BAWSEA configurations like this can bring to the HPM

antenna designer's table. Finally, it is worth noting that this particular example BAWSEA design has not been optimized; even better performance is likely attainable.

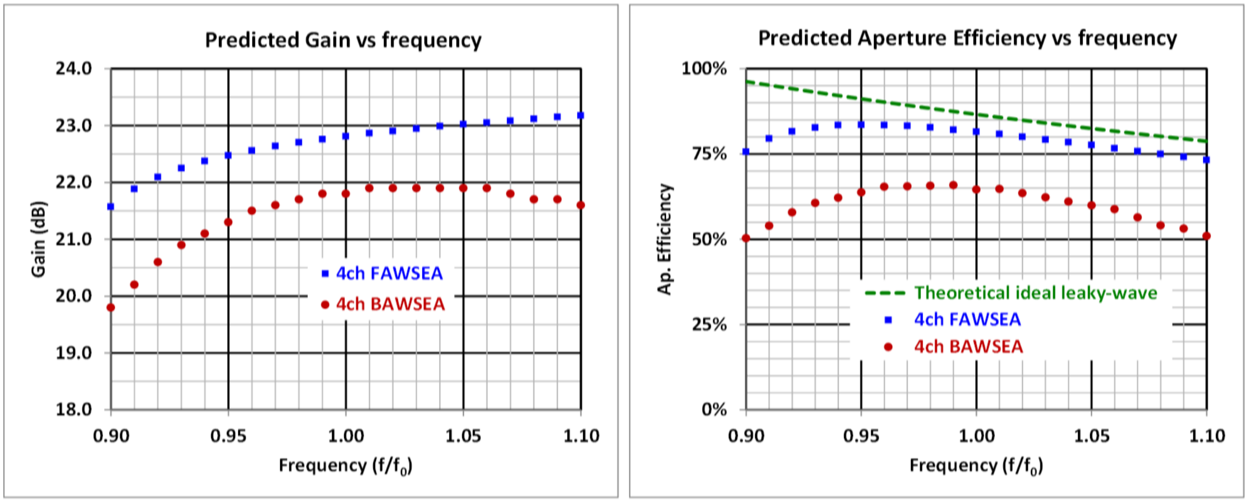

Figure 6. Comparison of Predicted Gain (left) and Aperture Efficiency (right) for the example 4-chan BAWSEA and our earlier recommended-design for a 4-channel FAWSEA.

4. DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

Research performed during this 6th quarter of the R&D program departed somewhat from the original plan, as we pursued an improved understanding of, and investigated the implications and opportunities offered by, the new BAWSEA configuration and related multiply-curved apertures. We are happy to report that predictions made with 3D BAWSEA full-wave RF models confirm that excellent performance should indeed be achievable in these configurations.

SARA's presentation (March 4, 2015) at the recent DEPS conference generated additional attention, recognition, and appreciation within the HPM DEW community of the especially-valuable capabilities offered by low-profile HPM-capable leaky-wave antennas.

Our ability to investigate more complex geometries of interest can be improved via application of more powerful computational resources; we will be taking significant steps in that direction very shortly.

As always, we appreciate ONR's continuing support for this R&D.

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